Sea Surface Height Variability in the Kuroshio Extension

Amy L. Fearing,[1] Kathleen A. Donohue, and D. Randolph Watts

Graduate School of Oceanography, University of Rhode Island, Narragansett, Rhode Island

Abstract. As part of the Kuroshio Extension System Study, an array of current and pressure recording inverted echo sounders (CPIES) was moored in a 600 km X 600 km region centered near 35N 146E off the eastern coast of Japan. This array measured bottom pressure and currents as well as round trip acoustic echo time from the seafloor to the surface from May 2004 through June 2006. With this array, we can calculate sea surface height (SSH), and thereby track currents, its meanders, the eddies it forms, and how they interact. The acoustic echo time is used to calculate the steric, or heat-content, variations in SSH. Bottom pressure is used to calculate the mass-loading variations in SSH. Satellite altimeters also monitor SSH and here we compare these measurements with CPIES derived SSH. There is a mapped product with a resolution of 3.5 days which combines all satellite data and interpolates over space and time. We also used Jason-1 along track data, with a temporal resolution defined by the satellite repeat of 10 days. Standard deviations and correlations were computed for both parts of SSH, as well as the total SSH measured by the CPIES and the altimeter. It was found that the correlation between the altimeter SSH and CPIES SSH is best where the signal amplitude and variance is highest. The correlations improve when SSH is low-pass filtered with a 40 day cutoff. The Jason-1 along track data provides better correlations to CPIES sites directly on its tracks, with an average value of r = 0.914, than the mapped altimeter data which had an average value of r = 0.886.

1. Introduction

Off the east coast of Japan, the Kuroshio western boundary current forms a vigorously meandering free jet known as the Kuroshio Extension. The Kuroshio Extension separates the cold northern waters from the warm, southern, subtropical waters of the recirculation gyre. The difference in sea surface height across the width of the current can be greater than a meter. This region is very active.

As part of the Kuroshio Extension System Study (KESS), the first cruise in May 2004 deployed an array of 37 current and pressure recording inverted echo sounders (CPIES) and 9 pressure recording inverted echo sounders (PIES). They array was located in a 600 km X 600 km region centered near 35N 146E as seen in Figure 1. This array measured bottom pressure and currents as well as round trip acoustic echo time from the seafloor to the surface from May 2004 through June 2006. During June 2005, a mid-experiment cruise used pulse delay telemetry to retrieve the first year's data from the instruments. The recovery cruise in June 2006 retrieved the CPIES. Here we compare SSH derived from the CPIES array to two satellite SSH products.

2. Data

2.1. CPIES data

This study utilizes the first year of data from 35 CPIES and 9 PIES within the KESS array (Figure 1). The time series are about 400 days long. All of the instruments were bottom mounted at depths between 5000m and 6000m. The daily average round trip acoustic echo time (τ) and daily average bottom pressure (P) were recorded and telemetered during the second cruise.

2.2. Satellite altimeter data

Satellite altimeter products were produced by Ssalto/Duacs and distributed by Aviso, with support from Cnes. The gridded absolute dynamic topography maps with resolution of 3.5 days were correlated with the CPIES measured SSH. The gridded products during this time period combine data from ERS, Jason-1, and Topex/Poseidon. The gridded data is every third of a degree. The Jason-1 along-track data was also used to

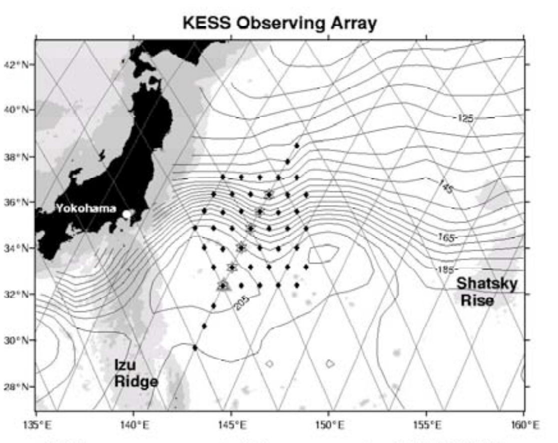

Figure 1. KESS Observing Array. Diamonds indicate locations of CPIES. Gridded black lines indicate Jason-1 ground tracks. Contour lines are mean surface dynamic height in dyn~cm (Teague et al., 1990). The 2000 and 4000~m isobaths are shaded dark and light gray, respectively. The stars are moored profilers from Woods Hole Oceanographic Institution. The triangle is the Kuroshio Extension Observatory from the National Oceanic and Atmospheric Administration's Pacific Marine Environmental Laboratory.

[1]Rensselaer Polytechnic Institute, Troy, NY

compare to sites located on those lines. These measurements were also absolute dynamic topography, with temporal resolution defined by the satellite repeat every 10 days. The Jason-1 satellite tracks are every 0.03 degrees longitude and 0.05 degrees latitude.

3. Methods

3.1. Computing sea surface height

3.1.1. Steric effects. Using measured τ values, GEM lookup tables provide temperature and salinity as a function of pressure that are used to calculate the geopotential height anomaly, Φ (Meinen and Watts, 2000). The steric part of SSH is then calculated as Φ/g, where g is gravity.

3.1.2. Mass-loading effects and the 'common mode'. The mass-loading contribution to SSH is $P/(\rho g)$, where P is the leveled deep pressure at a reference pressure of 5000 dbars and ρ is the density. There was a 'common mode' with ~0.2dbar range on 2 to 30 day timescales in the deep pressure values caused by atmospheric forcing. The common mode was removed from the mass-loading part of SSH.

3.2. Comparing CPIES SSH to altimeter SSH

The values of steric and mass-loading sea surface heights are then interpolated to the same times as the AVISO SSH maps and along-track data. Total sea surface height (η) is then computed, and is given by:

$$\eta = \Phi/g + P/(\rho g) \qquad (1)$$

Standard deviations are computed for each part of SSH, the CPIES total SSH, and the altimeter SSH measurements. Correlation coefficients between all of these are computed as well.

4. Results

The major part of SSH is steric. The mass-loading effects can have important contributions, but always have a much smaller amplitude than the steric effects.

Figures 2A and 2B show the standard deviations of the

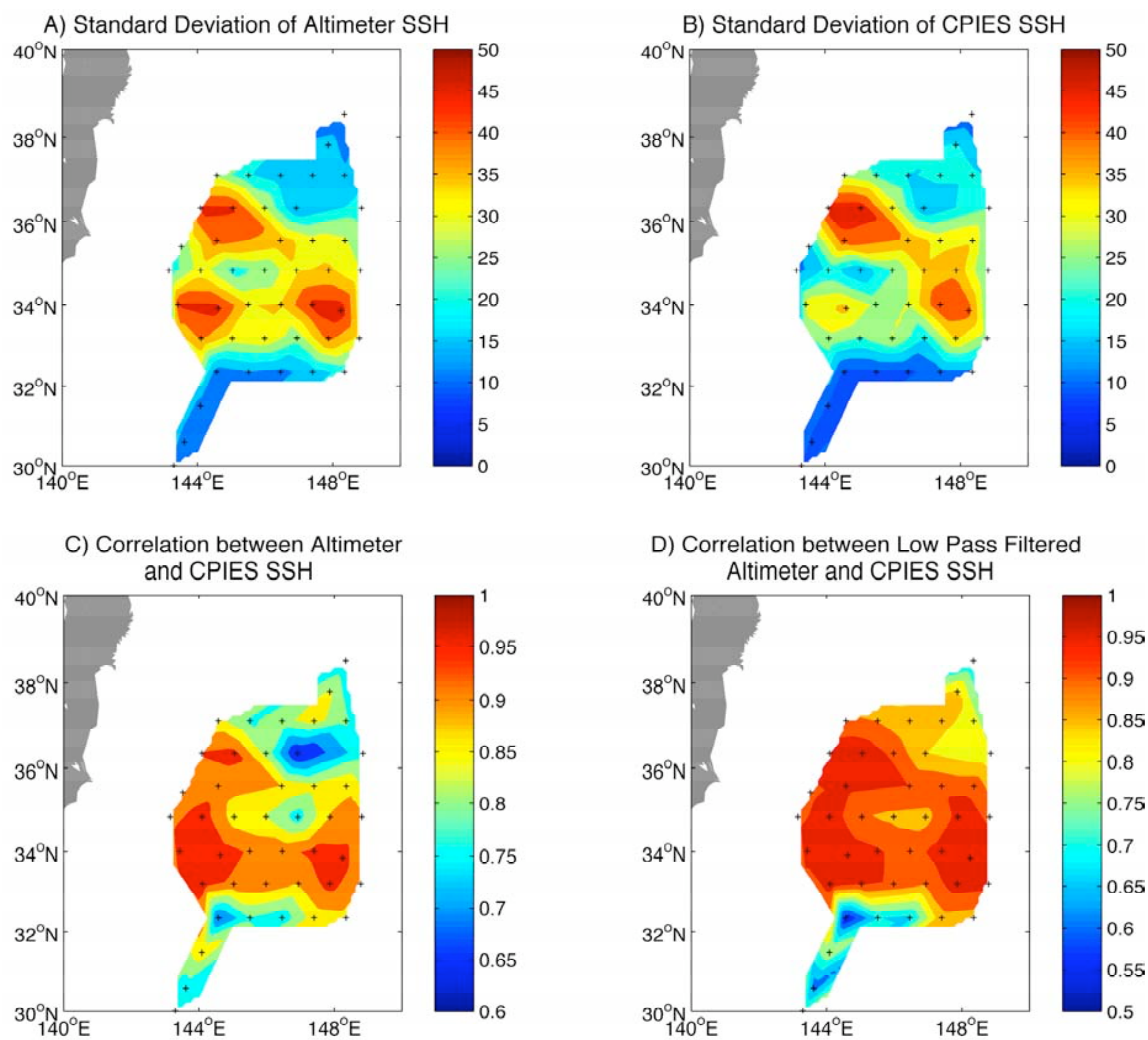

Figure 2. A. Standard deviation of altimeter SSH in cm. B. Standard deviation of CPIES total SSH in cm. C. Correlation coefficient of altimeter and CPIES SSH. D. Correlation coefficient of 40 day low-pass filtered altimeter and CPIES SSH.

satellite SSH signals and CPIES SSH signals, respectively. The highest values are in the middle of the array, which is where the Kuroshio Extension is meandering for most of the year. The lower variances, and consequently lower standard deviations, are in the northern and southern sections of the array. The two maps agree well with the exception of the southwest corner. In this region, the altimeter has higher variance than the CPIES SSH. This stronger signal can be seen in the time series of site F1, shown in Figure 3A.

The correlation coefficient (r) between the altimeter measurements of SSH and the CPIES measurements of SSH is shown in Figure 2C. The higher correlations are in areas which also have a higher variance. In the middle of the array, there is one site (E5), which has a lower r value, but had a high standard deviation. When examining the time series (Figure 3B), during the first 100 days of the deployment there is a higher frequency signal that the CPIES is detecting that the altimeter is missing. The next step was to low-pass filter the SSH data with a second order Butterworth filter and try to separate out the higher frequency signal. A 40-day cutoff for the Butterworth filter was used. Correlation coefficients were again computed between the altimeter and CPIES data. The results of this filtering are shown in Figure 2D. The correlations improved at E5, as well as in the northern section of the array. However, it still didn't improve the southern tip of the array, where there were the lowest standard deviations.

Most of the CPIES in the array lay on Jason-1 ground tracks (Figure 1). These sites were also correlated directly to the Jason-1 along-track data. Figure 4 shows the correlated values with the along-track product and the gridded product. The average correlation for sites directly on these lines compared with the along-track product is 0.914. The average for the same sites array when compared with the gridded data product is 0.886. Points off of Jason-1 tracks have an average correlation of only 0.869. However, these correlation values are all much higher than those found in the Gulf of Mexico, which had an average correlation of 0.77 for the 5 sites which were coincident with the Jason-1 ground tracks (Donohue et al., 2006).

5. Conclusions

The altimeter measurements of SSH agree well with the CPIES measurements. This correlation is best when the variance in SSH is high. Low-pass filtering both the altimeter and CPIES data improves the agreement when the variance is high. Using sites along the Jason-1 ground tracks and comparing this data directly to the Jason-1 data has better correlations than comparing these sites with the

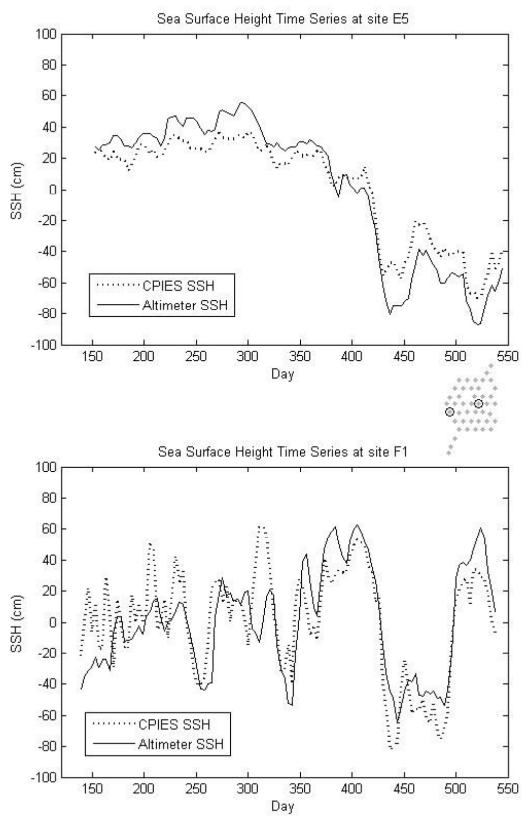

Figure 3. A. Time series of site F1, which is the site on the left which is circled on the schematic of the KESS array. B. Time series of site E5, which is the site on the right which is circled on the schematic of the KESS array.

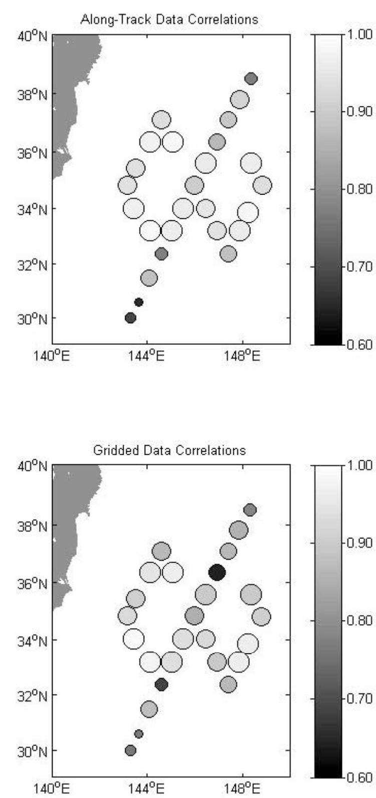

Figure 4. Correlations for sites that are coincident with Jason-1 ground tracks: A. with along-track altimetry data. B. with gridded altimetry data.

gridded altimeter product. In the future, studies may evaluate gridded products after Topex/Poseidon ceased to record data, and evaluate the seasonal influences on SSH signal amplitude. Knowing that the altimeter is measuring SSH well is important because this data extends back 20 years and covers all of the oceans, and is assimilated into current models and forecasts.

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Amy L. Fearing, Kathleen A. Donohue, and D. Randolph Watts, Graduate School of Oceanography, University of Rhode Island, Narragansett, RI 02882. (fearia@rpi.edu, kdonohue@gso.uri.edu, rwatts@gso.uri.edu)